SUMMARY OF OVERALL COMMISSIONING STRATEGY FOR PROTONS

R.Bailey, CERN, Geneva, Switzerland

Abstract

After a brief reminder of the various requirements on the LHC, the strategy for a staged commissioning with protons is summarised. Typical machine parameters and associated performance levels are given for each stage. Dedicated runs with ions and protons are mentioned, and how machine operation may be scheduled through a year is shown.

INTRODUCTION

Getting to nominal LHC conditions is not going to be easy. While the injectors have demonstrated that they can produce the required beams, the filling schemes are rather complex and will need careful commissioning. In the LHC ring, emittance conservation has to be mastered through the injection process, the energy ramp and the beta squeeze, and with almost 3000 bunches per beam a crossing angle is needed to minimise unwanted beam-beam interactions. Last but not least, the stored energy of 362MJ per beam is some two orders of magnitudes above that achieved at other machines, and will have to be approached with the utmost care.

Performance estimates given are based on the standard luminosity equation

$$L = \frac{N^2 k_b f \gamma}{4\pi\varepsilon_n \beta^*} F$$

where N is the number of protons per bunch, k_b the number of bunches per beam, f the revolution frequency, γ the relativistic factor, ε_n the normalised emittance, β^* the value of the betatron function at the interaction point, and F the reduction factor caused by the crossing angle, which is 1 for head on collisions and about 0.85 for the nominal crossing angle according to

$$F = 1 \Big/ \sqrt{1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2}$$

where θ_c is the crossing angle, σ_z the bunch length and σ^* the transverse beam size at the IP.

GLOBAL REQUIREMENTS

The LHC machine will have numerous clients to satisfy [1]. For ATLAS and CMS we need a strategy to get to proton collisions at 7TeV with a nominal luminosity of 10^{34} cm^{-2}s^{-1}. LHCb require a nominal luminosity in the region of 5 10^{32} cm^{-2}s^{-1} at point 8, while for ALICE a luminosity at point 2 of 10^{30} cm^{-2}s^{-1} is around optimum with protons. In points 2 and 8 the beta functions are tuneable in order to meet these needs as a function of the beam intensity. In point 2 transverse beam separations will also be needed to maintain the luminosity below an acceptable level for ALICE with higher intensities.

The high luminosity experiments will eventually have to handle almost 20 events per beam crossing. However, it will take time to learn how to do this and during early running they request that the event pileup is limited to 2 events per crossing. Similarly LHCb is designed for around 1 event per crossing and so significant event pileup should be avoided here also.

For ion running ALICE will require data at various energies and during this mode of operation ATLAS and CMS will also take data. Finally TOTEM request proton collisions at various energies and with special optics.

A STAGED APPROACH

It is clear from the above that both machine and experiments will have to learn how to stand running at nominal intensities. An early aim is to find a balance between robust operation and satisfying the experiments. Robust operation means avoiding quenches and at all costs damage. Satisfying the experiments means delivering integrated luminosity without significant event pileup.

To avoid quenches three parameters are considered:

- Higher β^* in IP 1 and 5 to avoid problems in the later, delicate part of the beta squeeze.
- Lower total current either by reducing the number of bunches or the bunch intensity, or both.
- Lower energy to provide more margin against transient beam losses or against magnets operating close to their training limits.

Event pileup ~ N^2/β^* and hence lower bunch currents also ensure that this is also acceptable except for very low betas.

With lower currents in mind, two important machine systems will be staged. For the collimators, a phased approach will be adopted which will provide the necessary protection but will require higher beta functions or lower currents. For the beam dump, 4 out of 10 dilution kickers will be installed for each beam, which will restrict the total circulating intensity to around 50%.

The resulting proposal for early proton running is to aim for a pilot physics run with a few tens of bunches per beam, and the commissioning strategy has been developed with this in mind. Following this, attention will shift to many-bunch operation, first with 75ns spacing and later with 25ns spacing.

Stage 1 – Pilot physics run

The aim here is to bring two moderate intensity beams to high energy and to collide them for physics. The target is 43 on 43 bunches of 3 to 4 10^{10} protons at 7TeV. The energy may be lower for reasons of overall machine reliability, as dictated by the performance of the magnets at high field with beam.

In order to provide collisions in LHCb, a certain number of bunches in one beam will be displaced by 75ns. The number of displaced bunches can vary from fill to fill if required, but it should be noted that increasing the number of bunches colliding in LHCb results in an equivalent reduction in the luminosity of the other experiments. Alternatively dedicated runs could be made for LHCb, but of course without collisions in the other experiments.

Initial physics will be with the injection optics. Once this has been achieved the squeeze will be partially commissioned.

The commissioning phases foreseen to achieve this [2] are summarised in Table 1.

Table 1: Commissioning phases for pilot physics

1	Transfer and injection
2	First turn
3	Circulating beam
4	450GeV – initial commissioning
5	450GeV – consolidation
6	450GeV – 2 beam operation
7	Switch to nominal cycle
8	Snapback – single beam
9	Ramp – single beam
10	Single beam to physics energy
11	Two beams to physics energy
12	Physics – no beta squeeze
13	Commission squeeze – single beam
14	Physics with partially squeezed beams

At each of these phases, a number of activities will be pursued in an iterative manner;

- Equipment commissioning with beam
- Machine protection systems
- Instrumentation
- Checks with beam (polarity checks)
- Measurements with beam (optics checks)

The luminosities expected for this pilot run are shown in Table 2, where a beta squeeze to 2m in IP1 and IP5 is supposed with 43 bunches of 4 10^{10}.

Table 2: Performance expectations during the pilot physics run

Pilot physics run	
Beam energy (TeV)	6.0, 6.5 or 7
Number of particles per bunch	4 10^{10}
Number of bunches per beam	43
Crossing angle (μrad)	0
Norm. transverse emittance (μm rad)	3.75
Bunch length (cm)	7.55
Beta function at IP 1, 2, 5, 8 (m)	2,10,2,10
Luminosity in IP 1 & 5 ($cm^{-2}s^{-1}$)	~5 10^{30}
Events per crossing in IP 1 & 5	0.76
Luminosity in IP 2 & 8 ($cm^{-2}s^{-1}$)	~ 1 10^{30}
Transverse beam size at IP 1 & 5 (μm)	31.7 (7TeV)
Transverse beam size at IP 2 & 8 (μm)	70.9 (7TeV)
Stored energy per beam (MJ)	2 (7TeV)

Note that the stored energy per beam of 2MJ, while significantly reduced compared to nominal, is still comparable to that of other facilities.

In this mode it is possible to increase the number of bunches to 156 per beam with a corresponding 4-fold increase in luminosity, still without the need for a crossing angle to avoid parasitic collisions. This should get us to 2 10^{31} $cm^{-2}s^{-1}$ in the high luminosity experiments. The insertion in IP8 could be tuned to increase the luminosity for LHCb. Luminosities in IP2 look to be good for ALICE. Tuning is possible if required.

If the experiments can stand the event rate, the bunch intensity could be pushed higher. With 156 bunches per beam at an intensity of 9 10^{10}, and all other parameters as in Table 2, a luminosity of 10^{32} $cm^{-2}s^{-1}$ is in reach.

It is also proposed at this stage to commission the crossing angle scheme, to see what effect this has on machine performance before the added complexity of parasitic collisions comes into play.

A number of questions are still open;

1. Do the experiments need single beam runs at 450GeV?
2. Should we provide collisions at 450GeV? ALICE has requested this.
3. Should we use a low energy cycle for machine setup, in order to reduce the turnaround time?
4. First high energy collisions will be 1 on 1 to provide data in points 1 and 5. A minimum of 2 on 2 is needed to provide collisions in points 2 and 8. What we should we do next? Trains of 4 can be provided with just 1 SPS cycle needed to fill each LHC ring, using the 43 bunch injection scheme. Similarly trains of 16 can be provided with just 1 SPS cycle per ring, using the 156 bunch injection scheme. Both of these scenarios would keep the LHC injection plateau as short as possible. 12 SPS cycles are needed to fill each LHC ring with either 43 or 156 bunches.

Stage 2 – 75ns operation

Once the pilot physics run is complete as described, a period of operation with 75ns spacing in proposed. There are several advantages to this [3];

- The reduced number of parasitic beam-beam encounters allows a relaxed crossing angle. This would be exploited, moving to the full crossing angle only in preparation for 25ns operation
- Electron cloud is not expected to be a problem
- Total beam intensities and power are increased in an incremental way, allowing the machine protection systems to adapt.

Initial operation at 75ns would be with the β^* achieved in the pilot physics run, say 2m, and a crossing angle of 250μrad. In this mode the beta squeeze would be pushed as far as possible. A typical performance expected is given in Table 3.

Table3: Performance expectations with 75ns operation

75ns operation	
Beam energy (TeV)	6.0, 6.5 or 7
Number of particles per bunch	$4\ 10^{10}$
Number of bunches per beam	936
Crossing angle (μrad)	250
Norm. transverse emittance (μm rad)	3.75
Bunch length (cm)	7.55
Beta function at IP 1, 2, 5, 8 (m)	1,10,1,10
Luminosity in IP 1 & 5 ($cm^{-2}s^{-1}$)	$\sim 2\ 10^{32}$
Events per crossing in IP 1 & 5	1.4
Luminosity in IP 2 & 8 ($cm^{-2}s^{-1}$)	$\sim 2\ 10^{31}$
Transverse beam size at IP 1 & 5 (μm)	22.4 (7TeV)
Transverse beam size at IP 2 & 8 (μm)	70.9 (7TeV)
Stored energy per beam (MJ)	42 (7TeV)

Stage 3 – 25ns operation I

In this mode with bunch intensities in excess of 3 to 4 10^{10} protons beam scrubbing may be needed. Otherwise the transition should be fairly smooth with moderate currents.

Table 4 shows the performance level possible up to the intensity limits resulting from the staging of collimators and beam dump. A luminosity of 10^{33} $cm^{-2}s^{-1}$ for the high luminosity experiments is in reach. Luminosities for LHCb in IP8 are now fairly optimal with the injection optics, while in IP2 detuning and transverse beam separation will be required for ALICE.

Stage 4 – 25ns operation II

Once the performance levels for Phase I have been achieved, installation of the full complement of beam dump dilution kickers and of the Phase II collimators will need to be scheduled. Following this, bunch intensities will be progressively increased toward nominal. Finally, the last part of the beta squeeze will need to be brought into operation before nominal performance is achieved.

Table 5 shows nominal performance.

Table 4: Performance expectations with Phase I 25ns operation

25ns operation with Phase I collimators	
Beam energy (TeV)	6.0, 6.5 or 7
Number of particles per bunch	$5\ 10^{10}$
Number of bunches per beam	2808
Crossing angle (μrad)	285
Norm. transverse emittance (μm rad)	3.75
Bunch length (cm)	7.55
Beta function at IP 1, 2, 5, 8 (m)	1,10,1,10
Luminosity in IP 1 & 5 ($cm^{-2}s^{-1}$)	$\sim 1\ 10^{33}$
Events per crossing in IP 1 & 5	2.1
Luminosity in IP 2 & 8 ($cm^{-2}s^{-1}$)	$\sim 1\ 10^{32}$
Transverse beam size at IP 1 & 5 (μm)	22.4 (7TeV)
Transverse beam size at IP 2 & 8 (μm)	70.9 (7TeV)
Stored energy per beam (MJ)	157 (7TeV)

Table 5: Nominal performance (Phase II 25ns operation)

Nominal parameters	
Beam energy (TeV)	7
Number of particles per bunch	$1.15\ 10^{10}$
Number of bunches per beam	2808
Crossing angle (μrad)	285
Norm. transverse emittance (μm rad)	3.75
Bunch length (cm)	7.55
Beta function at IP 1, 2, 5, 8 (m)	0.55,10,0.55,10
Luminosity in IP 1 & 5 ($cm^{-2}s^{-1}$)	$1\ 10^{34}$
Events per crossing in IP 1 & 5	19.2
Luminosity in IP 2 & 8 ($cm^{-2}s^{-1}$)	$5\ 10^{32}$
Transverse beam size IP 1 & 5 (μm)	16.7
Transverse beam size IP 2 & 8 (μm)	70.9
Stored energy per beam (MJ)	362

DEDICATED RUNS

TOTEM

The TOTEM experiment will measure the total pp cross-section and study elastic proton scattering, and is also interested in the study of diffractive events. This results in various run scenarios, most of which require a particular machine configuration that is considerably different from the standard configuration in IP5. The experiment suggests several runs, typically of one day duration, spread throughout the first years of machine operation. Furthermore the total-cross section measurements should begin in the initial phase of LHC operation.

While these runs are expected to be short, requiring perhaps just one substantial physics coast per measurement, the time to switch in and out of this mode of operation should not be underestimated. The experience with LEP polarisation runs shows that 2-3 shifts should be allocated for preparation and recovery each time. Furthermore, considerably longer will be needed to commission the new optics with tight beam conditions the first time it is tried on the machine, and to understand how to safely operate the Roman pots located either side of IP5.

Ions

The ALICE experiment has requested a short run with ions as early as possible. As with TOTEM running, the time to prepare for this mode of operation should not be underestimated, particularly the first time it is tried.

The first ions runs will be made using the so-called "early ion scheme", which foresees 62 bunches per beam and a β^* of 1m in IP2. With all other parameters as nominal, the performance levels that can be expected under these conditions are about a factor 20 (10 from the number of bunches and 2 from the beta) below the nominal luminosity for ion operation of 10^{27} $cm^{-2}s^{-1}$.

SCHEDULING

Every year a long shutdown will be needed by several machine groups for equipment servicing and major preventive maintenance [4]. The length of time estimated varies up to a maximum of 16 weeks, with some interdependence between the various activities. This fits with the requirements of the ALICE, ATLAS and CMS experiments, which also require an annual shutdown of 3-4 months.

Recovery from a long shutdown will need some time, firstly without beam (Machine Checkout, 4 weeks) and then with (Setup with Beam, 2 weeks).

Once the machine has been restarted after the annual shutdown, operation with beam will be interrupted by short stops for equipment repair and minor preventive maintenance. For the latter, the machine groups have given their requests [4], and a 3 day technical stop should be planned every month. Equipment groups can then plan the necessary activities, for which the necessary tools are available and should be used. Maintenance work using outside contracts needs particular attention.

After each technical stop, it will take time (between a shift and a day) to re-establish machine performance.

It will be necessary during the first years of running to allocate a significant amount of Machine Development. Based on the experience with LEP, some 15% of the available time will be devoted to studies.

Taking into account shutdowns, machine checkout, setup with beam, scrubbing runs, technical stops, restarts and machine development time, there will be around 150 days left for physics in a normal year. This will be used for proton luminosity running and to accommodate dedicated runs with ions and for TOTEM.

REFERENCES

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